

## LOW AND INTERMEDIATE ENERGY HEAVY ION COLLISIONS IN THE SEMI-CLASSICAL MICROSCOPIC DESCRIPTION

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**Résumé :** Cette contribution est consacré à la description des collisions centrales et périphériques à l'aide d'une dynamique Landau-Vlasov. Pour les collisions périphériques aux énergies intermédiaires, les corrélations masse-masse, les énergies moyennes des quasi-projectiles et les distributions angulaires sont obtenues et comparés avec les données expérimentales. Pour les collisions centrales, on montre que la fenêtre de fusion de TDHF à basse énergie disparaît avec l'introduction d'une interaction résiduelle. Au-delà de 20 MeV/u, la fusion incomplète est décrite avec le transfert d'impulsion et les déformations nucléaires associées. Le couplage aux états du continuum est analysé dans les dynamiques Vlasov et Landau-Vlasov. L'interaction Coulombienne étant incorporée, nous présentons des résultats sur le transfert d'isospin et l'excitation du mode dipolaire isovectoriel au voisinage et au-dessus de la barrière Coulombienne. Quelques perspectives pour l'étude d'observables physiques sont finalement tracées.

**Abstract :** It is shown how peripheral and central heavy-ion collisions can be described by Landau-Vlasov dynamics. For peripheral collisions at intermediate energies, mass-mass correlations, ejectile mean energies and angular distributions are obtained and compared with fragmentation data. For central collisions, one shows that the collision term destroys the TDHF property of transparency at low impact parameters for collisions close from the Coulomb barrier. Above 20 MeV/u incomplete fusion is described with associated linear momentum transfer and nuclear deformations. One exhibits how coupling to the continuum is obtained in Vlasov and Landau-Vlasov dynamics. Coulomb interaction being taken into account, we present also results concerning the isospin transfer and the excitation of the isovector dipole mode near and well above the Coulomb barrier. Some perspectives to further studies of physical observables are finally drawn.

### Introduction

The nuclear Vlasov and Landau-Vlasov equations have been introduced in order to follow the time evolution of the microscopic one body distribution function  $f(\vec{r}, \vec{p})$  in the phase space symplectic manifold defined at the Hartree-Fock and extended Hartree-Fock level. Properties and procedures for the determination of

approximate solutions have been widely discussed during this conference, especially in the B. Remaud's talk. In the table I, we sketch the salient features characterizing the two main approaches to these nuclear kinetic equations available in the literature. A nice derivation of these equations can be found, on the other hand, in R. Malfliet's contribution and in reference [1]. It turns out that the real and imaginary parts of the  $g$ -matrix enter in the mean field term and the collision term respectively. The energy and density dependence of the effective nucleon-nucleon interaction finds there its justification when one deals with the Landau-Vlasov equation.

Table I - Approaches to the nuclear kinetic equation : approximate solutions, ingredients and applications.

LANDAU-VLASOV (Ref. [2,3,4,5,6,7,18])	BOLZMANN-UHRLING-UHLENBECK (Ref. [8,9,10,11,12]) or VLASOV-UHRLING-UHLENBECK
Decomposition of one-body distribution function on a moving coherent state basis Initial nuclei in their ground state, each of them being an exact stationary solution of the Vlasov equation (initial self-consistent procedure)	Parallel ensembles of pseudo-particles (nucleons)  average over ensembles
Neutrons and protons ; Coulomb included ; simplified Skyrme interactions [2, 5] D1 interaction (long range correlations) [7]	Simplified Skyrme interaction  Momentum dependent force [13]
Uehling-Uhlenbeck collision term with : $\sigma_{nn}$ (energy, density, isospin) continuous relaxation	Uehling-Uhlenbeck collision term with : $\sigma_{nn}$ = constant continuous or fluctuating [14] relaxation
Slabs [5] Spherical symmetry [3] 3D - disintegration [6] Intermediate and low energy heavy ion collisions [4,18]	Intermediate and relativistic heavy ion collisions [8,9,10,11,12] $\pi$ and $\gamma$ emission [15] Multifragmentation [14]

The Vlasov equation is widely used in plasma physics where the mean-field is essentially given by the electromagnetic long range interaction. In our context (the heavy ion collisions), we note that the dominant term derives from the short range strong interaction, allowing a determination of the solution which is much more stable. In this contribution, we report on a few situations where these solutions were used in order to calculate physical observables and to characterize collision processes. The fragmentation mechanism in intermediate energy heavy ion collisions is analyzed (section 1). The occurrence of fusion-like processes is discussed in section 2. Particular attention is paid to particle emission in the continuum in section 3. In section 4, we mention some results concerning the excitation of isovector modes in heavy ion collisions near the Coulomb barrier.

### 1 - Fragmentation mechanism

As revealed by Landau-Vlasov calculations for collisions above 30 MeV/u, the main part of the reaction cross section goes into the projectile fragmentation cross section. As a matter of fact, the partial waves corresponding to deep inelastic processes at low energy contribute at intermediate energy to an abrasion-like mechanism. However different behaviour is found in high energy fragmentation [16] that has led to a model discussed in ref. 17. The figure 1 sketches target-like mass versus projectile-like mass correlations for the  $^{40}\text{Ar}$  (35 MeV/u) +  $^{27}\text{Al}$  system. A comparison with the geometrical abrasion model with a

reduced radius  $r_0 = 1.36$  fm which fits the data (ref. 16) shows that the microscopic description accounts properly for the main correlation characterizing a fragmentation process. The target-like recoil angle (in absolute values) versus projectile-like mass correlation at 44 MeV/u incident energy is described by the dashed area in figure 2 for the experimental data and by the full line for the calculations.

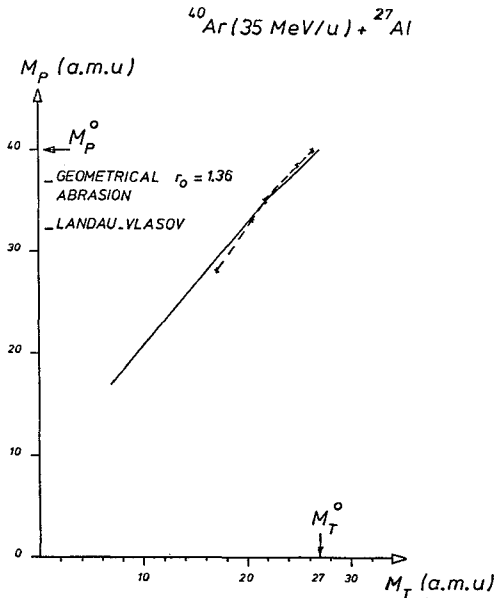


Figure 1 : Target-like versus projectile-like mass correlation in fragmentation reactions in the geometrical abrasion model (full line) and in the Landau-Vlasov calculation (dashed line) for the  $^{40}\text{Ar}$  (35 MeV/u) +  $^{27}\text{Al}$  reaction.

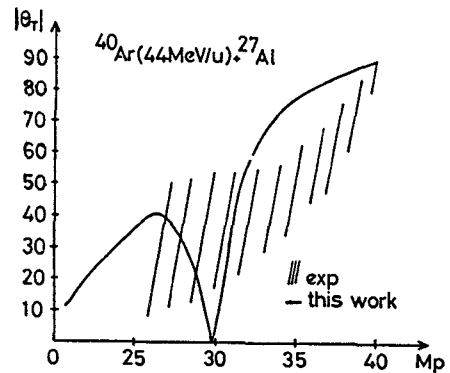


Figure 2 : Absolute value of the target-like recoil angle versus the projectile-like mass in  $^{40}\text{Ar}$  (44 MeV/u) +  $^{27}\text{Al}$  reactions. The Landau-Vlasov calculation (full line) is compared with the data of ref [16] (dashed area).

The dip of the calculated curve corresponds to a deflection towards negative angles. The orbiting has a twofold origin : first the attractive nucleus-nucleus force generated by the mean field ; secondly the one-body dissipation (nucleon exchanges) on the one hand and the two-body dissipation (collision term) on the other hand. For such peripheral reactions, it is worth mentioning that the nucleon-nucleon collisions act strongly at the surfaces of the interacting nuclei in order to damp the relative motion. The apparent discrepancy between data and calculations in figure 2 could find its origin in the strength of the two-body collision term as far as very peripheral reactions are concerned ( $A_p \sim 40$ ). Consequently, it seems relevant to ask for additional experimental data for a more precise analysis of this strength. For the mean energies of fragmentation products, one can mention that the agreement between theory and experiments is reasonable for the peripheral collisions. We refer the reader to the reference [18] for details.

## 2 - Fusion-like processes

A comparison between Vlasov and Landau-Vlasov calculations should answer the question dealing with the low  $l$ -window obtained so far in TDHF calculations (see ref. [19]). A renewal of this question was recently given by the experimental observation of a possible transparency in  $^{28}\text{Si} + ^{28}\text{Si}$  reactions at 12.4 MeV/u

(ref. [20]). The calculated time evolution of the relative distance  $R_{12}$  between the reaction partners in Vlasov dynamics indicates that such transparency could be present in absence of residual interaction (Fig. 3). Nevertheless, the same calculation performed in Landau-Vlasov dynamics shows that this effect is just an artefact of the TDHF approximation, as already mentioned by Tohyama et al. (ref. [21]) for the  $^{160}\text{O} + ^{160}\text{O}$  system.

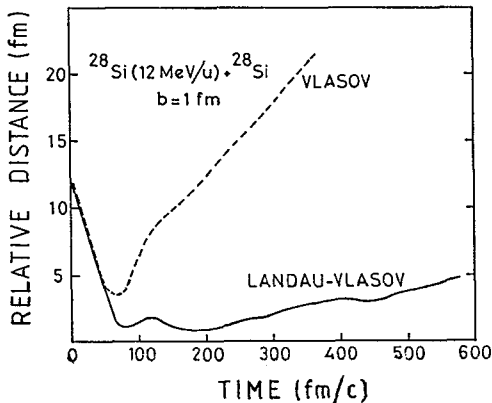


Figure 3 : A comparison between Vlasov (dashed line) and Landau-Vlasov (full line) calculations for the time dependence of the relative distance between interacting nuclei shows that the transparency in  $^{28}\text{Si}$  (12 MeV/u) +  $^{28}\text{Si}$  with a central impact parameter  $b = 1$  Fm is destroyed by the residual interaction.

In fact, the fusion process is very likely even at high bombarding energies (see the contribution of M. Pi in this conference), at least for medium and heavy systems. For very light systems like  $^{40}\text{Ar} + ^{27}\text{Al}$  a transparency is found again above 30 MeV/u as discussed in the ref. [4] and [12]. For the  $^{40}\text{Ar}$  (27 MeV/u) +  $^{238}\text{U}$  reaction, for instance, it is found that large deformations of the composite system (incomplete compound system) are induced for a long time lag. This feature (Fig. 4) combined with a reasonable estimation of the linear and orbital momentum transfers (ref. [22]) provides us some confidence in our microscopic description of fusion in this energy domain.

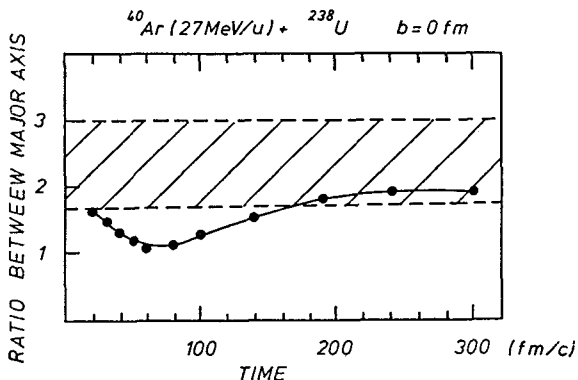


Figure 4 : Time dependence of the ratio between major axis for the composite system formed in the  $^{40}\text{Ar}$  (27 MeV/u) +  $^{238}\text{U}$  head-on collision. Landau-Vlasov calculations (full line) are compared with data of ref. [22] dashed line.

### 3 - Particle emission into the continuum

Vlasov and Landau-Vlasov dynamics allow a direct coupling into continuum states, as soon as large collective motions are involved. It can be seen by a determination of the flux of particles (neutrons and protons) crossing a spherical surface surrounding the nuclear system. For nuclear reactions like the  $^{40}\text{Ar}$  (27 MeV/u) +  $^{27}\text{Al}$  for example, the flux exhibits two components when time increases :

a preequilibrium component (large anisotropy and kinetic energy of the emitted particles) during the first stages of the collision and an evaporation component (isotropic and thermal kinetic energy of the particles). For the decay of a hot nucleus (ref. [23]), a burst of emitted particles is obtained during the first  $4 \times 10^{-22}$ s (for the  $^{40}\text{Ca}$  nucleus at 15 MeV temperature in the case of the fig.6).

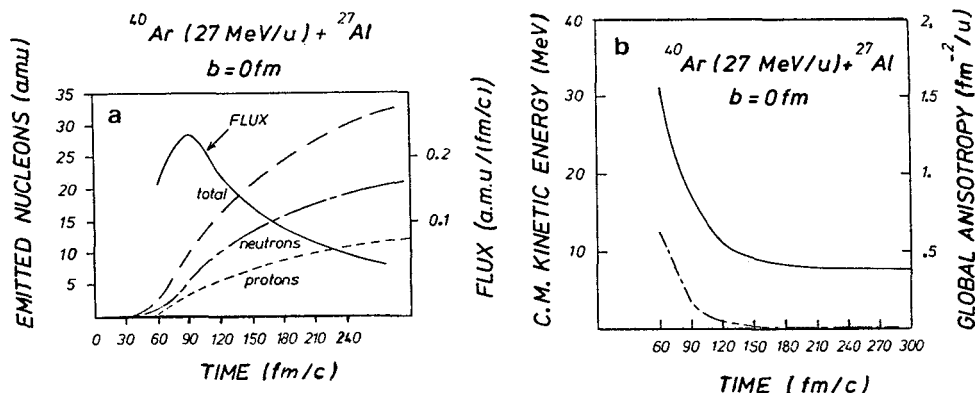
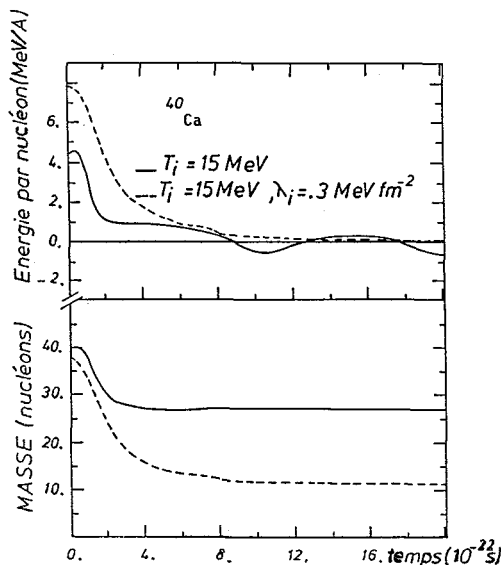


Figure 5 : (a) For a central collision, time evolution for the nucleon emission flux (right scale) and of the total number of emitted particles (left scale), respectively protons, neutrons and both.

Figure 5 : (b) For the same collision, time evolution of the instantaneous mean energy (left scale) and of the anisotropy factor (right scale) of the emitted nucleons.

Figure 6 : Decrease of the excitation energy per nucleon (upper part) and of the residual mass (lower part) of a  $^{40}\text{Ca}$  nucleus initially heated up to a temperature of 15 MeV (full lines) and simultaneously compressed (dashed lines).

The mass of the residual nucleus decreases smoothly afterwards, as obtained recently in spherical TDHF calculations (ref. [24]). The two previous situations illustrate that coupling into the continuum is naturally contained in our description, allowing predictions concerning light particle emissions and dynamical decays.



## 5 - Isospin transfer

The role of the isovector giant resonance of the composite system for the charge equilibration during heavy ion collisions was pointed out by the observation of the isobaric distributions in deep inelastic reactions (ref. [25]). Its excitation is revealed by TDHF calculations ([26,27]). In figure 7, the time evolution of the scalar product between the vector joining the neutron and proton center of mass respectively and an unitary vector along the line joining the center of mass of the

reaction partners is drawn for the  $^{16}\text{O}$  (5.5 MeV/u) +  $^{40}\text{Ca}$  reaction where the impact parameter  $b$  is equal to 6 fm. The longitudinal isovector dipole mode is excited in Landau-Vlasov as well as in Vlasov dynamics. A time shift between the two calculations is due to the surface collisions which favour the excitation for a smaller overlap of the nuclear densities in the Landau-Vlasov calculation than in the Vlasov case. These calculations, possible only because our description accounts for the Coulomb interaction, confirm that a collective mode whose characteristics have been calculated in ref. [28] is very likely responsible for the charge equilibration, at least during the first  $5.10^{-22}\text{s}$  (i.e. 150 fm/c).

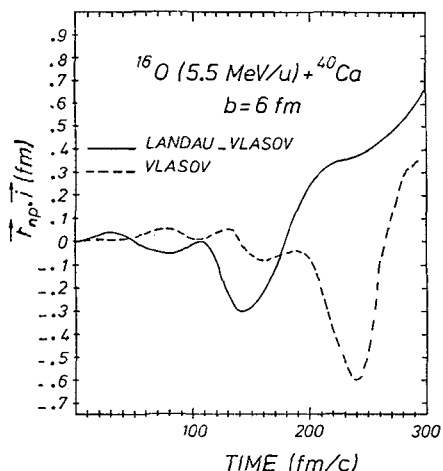


Figure 7 : Excitation of the longitudinal isovector dipole mode in  $^{16}\text{O} + ^{40}\text{Ca}$  reactions near the Coulomb barrier. The oscillations are obtained as well in Vlasov (dashed line) as in Landau-Vlasov dynamics.

## Conclusion

We have shown, with the help of a few examples, the richness of the semi-classical microscopic description for many physical situations occurring in low and intermediate heavy ion collisions. Further studies are in progress ; they concern giant resonances at zero and finite temperature, the implementation of the momentum dependent Gogny effective interaction, the fission process at finite temperature, the gamma and pion production, the fluctuations around mean values of observables. This general project is inspired by an utterance from Gandhi : "My quest for truth taught me the beauty of compromise".

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